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Analysis of High Sulfate Concentrations in Greater New York City Air

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Results showed that the current procedure for sampling sulfate every sixth day does not provide sufficient data for adequately determining how sulfate concentrations relate to meteorological phenomena. In particular, the sampling schedule is not sufficient for determining when prolonged periods of high sulfate concentrations begin and end. The sampling schedule only allows for indicating what the meteorological conditions were when the concentrations were a certain value and not how the concentrations changed with changing meteorological conditions.

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ANALYSIS OF HIGH SULFATE CONCENTRATIONS IN GREATER NEW YORK CITY AIR

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ABSTRACT

The meteorological phenomena occurring during April 15 to 21, 1976, when high sulfate concentrations were measured in the New York City area, are summarized. Findings of earlier investigations of relationships between meteorological phenomena and high sulfate concentrations are compared to the findings of this investigation. Since ozone readily occurs with the same meteorological conditions that are associated with sulfate episodes, the ozone concentrations are also discussed. Finally, the results of two other detailed investigations into correlations between meteorological phenomena and air pollution concentrations (sulfate and ozone) during mid-April 1976 over the northeastern United States are compared to the results of this investigation.

Results showed that the current procedure for sampling sulfate every sixth day does not provide sufficient data for adequately determining how sulfate concentrations relate to meteorological phenomena. In particular, the sampling schedule is not sufficient for determining when prolonged periods of high sulfate concentrations begin and end. The sampling schedule only allows for indicating what the meteorological conditions were when the concentrations were a certain value and not how the concentrations changed with changing meteorological conditions.

This report covers a period from December, 1978 to August, 1979 and work was completed as of August, 1979.

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SECTION 1

INTRODUCTION

Twenty-four-hour air samples, taken every twelfth day in the National Air Surveillance Network (NASN), are analyzed for sulfate (SO_4) by the U. S. Environmental Protection Agency (EPA). These samples are routinely supplemented by SO_4 samples collected by numerous State and local air pollution control agencies on every twelfth day, offset 6 days from the NASN schedule. Ideally, the combined operations of the EPA and the control agencies produce a record of SO_4 concentrations for every sixth day. For the investigator trying to understand the variations in SO_4 concentrations, the question arises, "How representative are these SO_4 data in regards to time and space?" In a separate report[1] discussing spatial representativeness, analysis of 2 years of daily SO_4 data from a four-station network in the New York City area indicated that SO_4 concentrations varied regionally over the area with station separations as great as 125 km.

In this report, the temporal representativeness of the current national sampling program is evaluated. Daily SO_4 data collected at a four-station network in the New York City area are examined for a selected episodic period (April 15 to 21, 1976). The meteorological conditions that prevailed throughout the episode are summarized. Those results are then compared to earlier investigations[2-13] relating SO_4 episodes to meteorological phenomena in order to determine what meteorological prerequisites characterized the duration and intensity of the SO_4 episode. Trajectory calculations are used to designate suspected upwind source areas of high SO_4 concentrations in the New York City area. In addition, supplementary SO_4 data are reviewed for locations upwind of the New York City area. The results of two independent investigations[2,14] of air pollution during April 15 to 21, 1976, also are compared to the results of this study.

SECTION 2

CONCLUSIONS

Analyses of SO_4 data from CHAMP stations in the New York City area and supplementary networks, plus a comparison of our results with earlier investigations[2-14] yielded the following conclusions:

The SO_4 episode, which persisted in the New York City area from April 15 to 21, 1976, was primarily associated with a meteorological phenomenon common to high SO_4 concentrations: a relatively warm, slow-moving, near-cloudless air mass (stagnating high pressure area). However, the SO_4 concentrations were high prior to the influx of very warm air and continued although the initial air mass was replaced by another. Either the replacement of the second SO_4-polluted air mass by a third air mass, or the precipitation associated with an active front caused the SO_4 episode to terminate.

Forty-eight-hour trajectories of air in the surface-to-1000-m layer, in conjunction with the limited SO_4 data, indicated that the high SO_4 concentrations could have resulted from long range transport. Further verification of this finding should be pursued through continuous sampling at potential upwind sites as well as at receptor sites.

The potential for photochemical reactions was great during a period of high ozone O_3 (>8 pphm) and SO_4 concentrations in the New York City vicinity.

A 6-day SO_4 sampling cycle provides insufficient data for adequately understanding the relationship between meteorological phenomena and sulfate concentrations. While an independent analysis[2] from the NASN for April 18, 1976, noted the severity of the episode in addition to the meteorological conditions associated with the worst conditions, data on the corresponding

meteorology during initiation or termination of the episode were lacking. In addition, the duration of the episode and the time-representativeness of the SO_4 observations could not be inferred.

An ozone investigation[14] coinciding with the sulfate episode in the New York City area concluded that the areas of high ozone concentrations corresponded to areas of low visibility. The results of our study cast doubt on the inference that gaseous ozone was the prime cause of reduced visibility. Use of the limited SO_4 data available for the eastern United States showed that areas of high SO_4 concentrations also corresponded to areas of restricted visibility. Until SO_4 concentrations are measured continuously, it will be difficult to evaluate the effects of this and other pollutants on visibility.

SECTION 3

BACKGROUND AND METHODS

SULFATE DATA

Sulfate was recognized as an air pollution hazard more than 25 years ago[15,16]. However, it was only with the publication of the Community Health and Environmental Surveillance System (CHESS) report[17] in 1971 that widespread interest in health hazards associated with high SO_4 concentrations was rekindled. Subsequent to that report, EPA published two documents[18,19] releasing data about SO_4 and presenting a strategy for investigating the SO_4 problem. Although the SO_4 data base was found inadequate[18], the papers did not recommend increasing the sampling frequency nor comment on the disadvantages of using discontinuous SO_4 observations. However, preliminary findings in one investigation[20] did indicate that more useful data would be collected if sampling was continuous, particularly for correlating high concentrations with specific meteorological phenomena.

The combined operations of the NASN, State, and local agencies are scheduled to determine SO_4 concentrations every sixth day. The standard procedure at individual monitoring sites is to collect a sample for each 24-hour period starting at midnight. The SO_4 measurement is made from a small strip of filter which collects suspended particulate via a high volume (Hi-Vol) air sampler. The strip of filter is extracted with water and a portion of the aqueous extract is analyzed for SO_4 by the methyl thymol blue method modified for use in the auto-analyzer. There is no standard for SO_4, but concentrations as low as 10 $\mu g/m^3$ (24-hour average) have been associated with adverse health effects in preliminary epidemiological health studies[17]. Since there is no additional documentation on possible hazardous SO_4 concentrations, 10 $\mu g/m^3$ or more is labeled high.

Daily SO_4 data came from the Community Health Air Monitoring Program (CHAMP) of the EPA. From January 1974 through June 1976, daily SO_4 data were collected from a network of four stations in the New York City vicinity. Three of the stations, those in Queens, Brooklyn, and the Bronx, were in New York City, and the fourth, at Riverhead, was 125 km east of the city. The locations of the stations are shown in Figure 1. These stations were operated in the same manner as a NASN station, the only difference was in the timing of filter changes. The filters in the CHAMP were changed 11 a.m. each day while the NASN operated its stations from midnight-to-midnight. There were many missing samples in the first 6 months of operation, so the data for that period were not evaluated.

Examination of the SO_4 data for July 1974 to June 1976, showed six periods of five or more consecutive days yielding high concentrations throughout the four-station network. The longest period was April 15 to 21, 1976. The SO_4 data for that period were selected for subsequent detailed examination and comparison with the SO_4 data from the NASN, State, and local agencies as well as the meteorological data. An earlier investigation[2] had summarized the meteorological phenomena associated with high SO_4 concentrations recorded by the NASN over the northeastern United States on April 18, 1976. These conclusions could be compared to those based on the daily 24-hour data of CHAMP. In addition, a second study[14] summarized the meteorological conditions for the period April 12 through April 23, 1976 that were associated with photochemically-produced ozone. The data from that investigation for O_3 are compared to the results found in this investigation for SO_4.

METEOROLOGICAL PHENOMENA PREVIOUSLY ASSOCIATED WITH HIGH SO_4 CONCENTRATIONS

Numerous meteorological phenomena have been associated with high SO_4 concentrations[2-13]. In an analyses of relatively large amounts of SO_4 and meteorological data, one group[3] found high temperatures (about 18°C, or 65°F, and greater) and high dew point temperatures (about 16°C, or 60°F, and greater) accompanied high SO_4 concentrations. A number of investigators[2,4,5] discovered that a high potential for photochemical reactions (inferred by

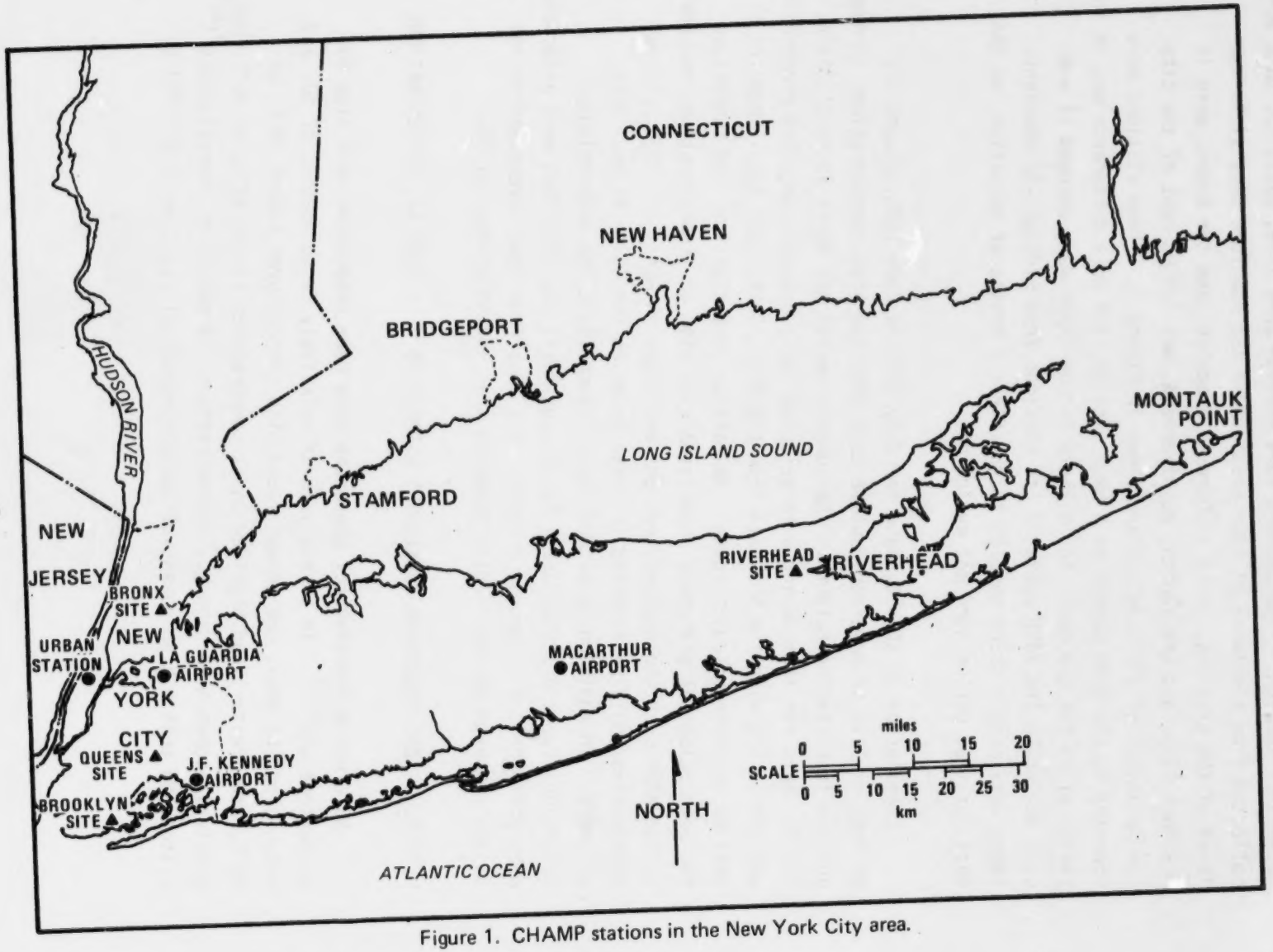

Figure 1. CHAMP stations in the New York City area.

abundant sunshine) was an important contributing factor to high SO_4 concentrations. Slow moving or stagnant air masses have previously been associated with high concentrations[2,4,5]. Furthermore, the oxidation of SO_2 to SO_4 occurs more readily at higher relative humidities[6,7], particularly at humidities of 70 percent or more[8]. Visibility reductions due to smoke and haze have been positively correlated with high SO_4 concentrations[9,10]. Visible plumes from large point sources have been observed at distances as great as 80 km[11]. Other plumes have been detected at distances of 160 km[12] and 400 km[11] from the source; the likely source-receptor relationships produced from visible plumes have been demonstrated by trajectory analyses[9,10]. Precipitation has been reported as the most effective means of removing SO_4 from the ambient air[13].

METEOROLOGICAL RESOURCES

Surface weather observations from four stations were examined: La Guardia Airport, Kennedy Airport, the Urban Station (Manhattan) in New York City, and Islip (MacArthur Airport 40 km west of Riverhead and 85 km east of New York City). The locations of these sites are shown in Figure 1. Observations which were evaluated included temperatures, sunshine*, wind direction and speed, relative humidity, weather (fog, haze, occurrence of precipitation), and amount of rainfall. Examination of the data from the four sites for the episode period indicated that there were only minor differences between stations, so the summarized data, with the exception of sunshine data, were solely from La Guardia Airport. The sunshine data were derived from the only station which records that variable, the Urban Station (the Urban Station does not record as many parameters as the other stations). A single episode of precipitation occurred on April 22 (0.16 in, or ~0.4 cm of rainfall) at La Guardia Airport.

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*Sunshine is recorded in percent and shows the observed duration of sunshine in minutes divided by the daily maximum possible number in minutes for a specific date.

Daily Weather Maps[21] of the United States, showing daily conditions at the surface and at 500 mb (about 5000 m above sea level) at 7 a.m. Eastern Standard Time (EST) were reviewed. These maps depict fronts, sea-level isobaric configurations, air flow aloft, and areas of precipitation.

Trajectory calculations[22] supplemented the data from the Daily Weather Maps by showing the likely paths of air parcels prior to their arrival in the New York City area. The trajectories are based on wind data from the rawinsonde observations scheduled at 7 a.m. and 7 p.m. EST each day. In the trajectory calculations, wind observations within a radius of 300 nautical miles (556 km) of the air parcel center are evaluated. A point along the trajectory is determined every 3 hours. Trajectories are started from a source or receptor four times daily, 1 and 7 a.m. and 1 and 7 p.m. In this report, backward trajectories were computed to reveal air movements in the surface- to 1000-m layer terminating over New York City. Trajectories were limited to 48 hours. Individual points along a trajectory indicate the general area, and not a precise location where air was located earlier.

SULFATE DATA IN UPWIND AREAS

In order to provide additional meaning, trajectory analyses data are discussed in conjunction with SO_4 concentrations in upwind areas. While there are shortcomings in the data, in regard to spatial coverage and the number of observations available on specific days, crude indications of source-receptor relationships can be implied. These supplementary SO_4 data include: 1) the NASN data for the northeastern United States for April 18, 1976; 2) the State and local data for April 12 and 18, 1976, for Maryland, New York and Ohio (some States have SO_4 data for April 18 that are excluded in the NASN data); 3) data from West Virginia and the Tennessee Valley Authority (TVA) network (stations in Alabama, Kentucky, Illinois, Tennessee, and Virginia) for various days from April 12 to 20, 1976; and 4) data for the Province of Ontario, Canada for April 12 to 22, 1976. The extensive network of sulfate monitoring stations in the Ohio River Valley, which operated on a daily basis for the Electric Power Research Institute in 1974 and 1975, was inoperative at this time.

COEXISTENCE OF HIGH SULFATE CONCENTRATIONS AND HIGH OZONE CONCENTRATIONS

High ozone concentrations are frequently synchronous with high SO_4 concentrations, particularly during meteorological conditions favoring photochemical reactions[3,5].

SECTION 4

DATA SUMMARIES, ANALYSES, AND COMPARISONS

SULFATE CONCENTRATIONS

CHAMP Network

The 24-hour concentrations of SO_4 at the four CHAMP stations for April 14 to 22, 1976, are listed in Table 1. To denote the relative severity of the episode (high concentrations from April 15 to 21) average concentrations for non-episodic days in 1976 and in April 1975 are listed. The filters, removed at 11 a.m. on April 14, showed that the Queens and Brooklyn sites had high concentrations while the Riverhead and Bronx sites did not. Concentrations were high at all stations on April 15, and gradually increased until they peaked on April 18 and 19. Thereafter, the concentrations gradually decreased and by April 22 the episode had terminated. Even though the Riverhead monitoring site was 125 km from the other three sites, it also recorded similar high concentrations.

NASN and State and Local Agency Stations

The 24-hour SO_4 concentrations for the every sixth day sampling cycle for April 1976 for sites in and close to New York City are listed in Table 2. There was little input (sampling on April 12 and 24) from local agencies. It is obvious that the NASN stations were operated near the time of peak concentrations (see Table 1) and that concentrations on April 18 averaged about three times higher than for other NASN sampling days in April.

TABLE 1. SULFATE CONCENTRATIONS ($\mu g/m^3$) AT CHAMP STATIONS IN THE NEW YORK CITY AREA, 4/14-22/76*

Date	Stations			
	Riverhead	Queens	Brooklyn	Bronx
4/14	7	11	10	7
4/15	10	15	12	14
4/16	M†	21	19	21
4/17	22	23	22	31
4/18	25	30	27	26
4/19	30	31	32	37
4/20	22	25	26	27
4/21	16	17	19	24
4/22	6	8	8	10
Non-episode 4/76	7	8	8	7
Average 4/75	6	6	7	6

* Note: Sample collected for 24-hour period ending at 11 a.m. for date listed

† M = Missing

TABLE 2. SULFATE CONCENTRATIONS ($\mu g/m^3$) AT NASN STATIONS IN THE NEW YORK CITY AREA, 4/76*

Date	Stations						
	New Haven, CT	Waterbury, CT	Elizabeth, NJ	Paterson, NJ	N.Y.C. (Harlem)	N.Y.C. (Welfare Island)	N.Y.C. (CCNY)
4/6	8	9	7	7	8	11	7
4/12†						6	
4/18	32	32	29	33	15	33	
4/24†							8
4/30	11	9	8	9	10	14	

* Sample collected for 24-hour period on listed day.

† Stations operated by local agencies.

Surface Weather Data In The New York City Area

The surface weather associated with the high SO_4 concentrations starting with the day before the observed high concentrations at all four CHAMP stations (Table 1), is summarized in Table 3. Since the filter is changed toward mid-day, the SO_4 data reported for a particular day must be compared to the prior as well as the listed day. The episode beginning on April 15 (Table 1), started with a period of marked warming, on a day showing wind speeds lower than the day before. Temperatures continued to increase until they were comparable to summertime temperatures, 14° to 15°C (25° to 27°F) above April normals. Thereafter, the concentrations decreased as the temperatures declined, but remained high through April 21. The average dew point temperature was only 2°C (36°F) on the first day with high SO_4 concentrations. When the concentrations peaked the dew point temperatures were lower than those associated with high SO_4 concentrations in a prior study[3]. The sunshine exceeded 95 percent throughout the episode. Winds were out of the southwest quadrant from the beginning of the episode until the concentrations peaked. Thereafter, the winds had an easterly component (from the Riverhead area toward New York City). Wind speeds ranged from 3 mph ($\sim$1.4mps) to 14 mph ($\sim$6.3 mps) and at the time of the peak averaged near 11 mph (5 mps). The relatively high resultant winds (compared to the average speeds) indicate that the winds were fairly persistent on those days. All relative humidities (eight observations daily) were below 70 percent for all days but one prior to the period of declining concentrations. Haze was present throughout the SO_4 episode. Rainfall occurred on April 22.

BROAD SCALE WEATHER FEATURES

The surface map for April 14 (Figure 2a) shows the meteorological pattern at the onset of high concentrations. The outstanding feature is the weak pressure gradient and high pressure area centered over the eastern United States. The center of this high was over Lake Michigan on April 12 and northwestern Ontario on April 11; the air mass originally came from Canada behind a rapidly moving vigorous cold front. Winds at the 500-mb level over the eastern United States on April 14 (Figure 2b) were out of the

TABLE 3. PERTINENT SURFACE WEATHER DATA AT LA GUARDIA AIRPORT, 4/76

(reported in units listed in published records)*

Date	Temperature (°F)				Total Sunshine (%)	Resultant Wind (mph)		Average Wind (mph)	Relative Humidity (%)		Visibility Obstruction**
	Maximum	Minimum	Depart. of avg. from normal	Average Dew Point	Urban site	Direction	Speed	Speed	Maximum	No. observations exceeding 69%	K = Smoke H = Haze F = Fog
4/13	62	40	0	18	100	28	13.7	14.1	36	0	
4/14	70	52	10	28	99	27	4.9	8.2	40	0	
4/15	75	51	11	36	96	21	4.9	7.5	59	0	KH
4/16	77	55	14	42	99	23	2.9	6.0	54	0	KH
4/17	88	58	21	54	100	20	3.4	6.5	73	2	H
4/18	91	68	27	55	99	21	8.5	10.8	66	0	KH
4/19	85	70	25	56	100	21	12.0	13.4	54	0	KH
4/20	84	60	10	57	96	16	1.3	9.4	78	2	KH
4/21	66	54	6	50	99	5	11.7	12.9	83	4	KH
4/22	68	51	6	54	31	7	5.5	11.4	90	8	FH

* Based on observations at 3-hourly intervals
Rainfall was limited to 0.16 inches on April 22.

** Reported only when visibility 6 miles or less.

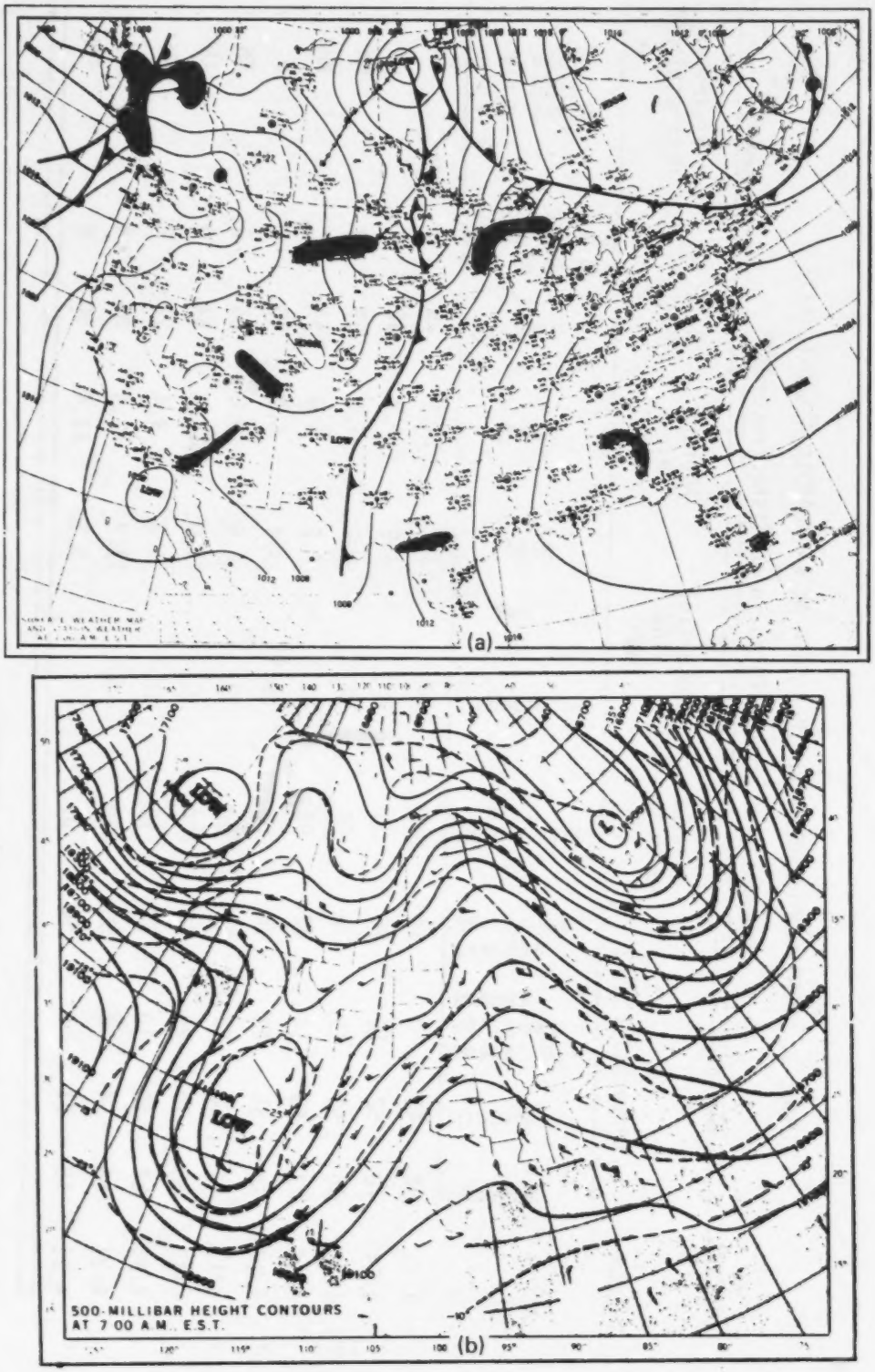

Figure 2. Daily weather maps for 4/14/76. (a) Surface weather map. (b) 500 mb map.

northwest and generally 30 knots or stronger. The change in surface and 500-mb maps from April 14 to the time of peak concentrations on April 19 was gradual. The surface weather map for April 18 (Figure 3a) shows a dominant high pressure feature over the eastern United States. At the 500-mb height on April 18 (Figure 3b), a high pressure area was centered over Virginia and caused light winds (generally 10 knots) over the eastern United States. Although surface maps revealed little change in the New York City vicinity from April 14 to 19, the map for April 20 (Figure 4a) indicated that a weak dissipating cold front would pass through New York City, bringing in prevailing westerly winds averaging about 13 mps (28.6 mph) over the northeastern United States. In spite of the frontal passage (accompanied by a 10° F drop in minimum temperature and a wind shift, but no rain and practically no clouds) and rapid air movement aloft on April 20, the SO_4 concentrations on April 21 were still high. The surface map for April 22 (Figure 5a) illustrates that meteorological conditions were changing as two fronts were approaching (both passed through the New York City area during the day). The 500-mb map for April 22 (Figure 5b) shows southwest winds of 15 to 20 mps (30 to 40 knots) over the New York area. Due to the advancing fronts, after midnight on April 22, there was drizzle, fog, and extremely low clouds with bases at 100 feet, and moist air (see Table 3).

Thus, the high SO_4 concentrations were initially associated with a rapidly moving air mass traveling from northwestern Ontario to the eastern Unites States. The air mass remained practically stationary from April 14 to 19, and SO_4 concentrations increased and peaked during that interim. After April 19, concentrations decreased as the high moved eastward but remained above 10 $\mu g/m^3$ for 2 days. The first change in air mass after April 18 brought in air from the west. Possibly because of its movement over a large SO_2 source area to the west and northwest[23], this air had a relatively high SO_4 concentration. After two additional changes in air mass and the passage of an active front, SO_4 concentrations finally decreased to relatively low values.

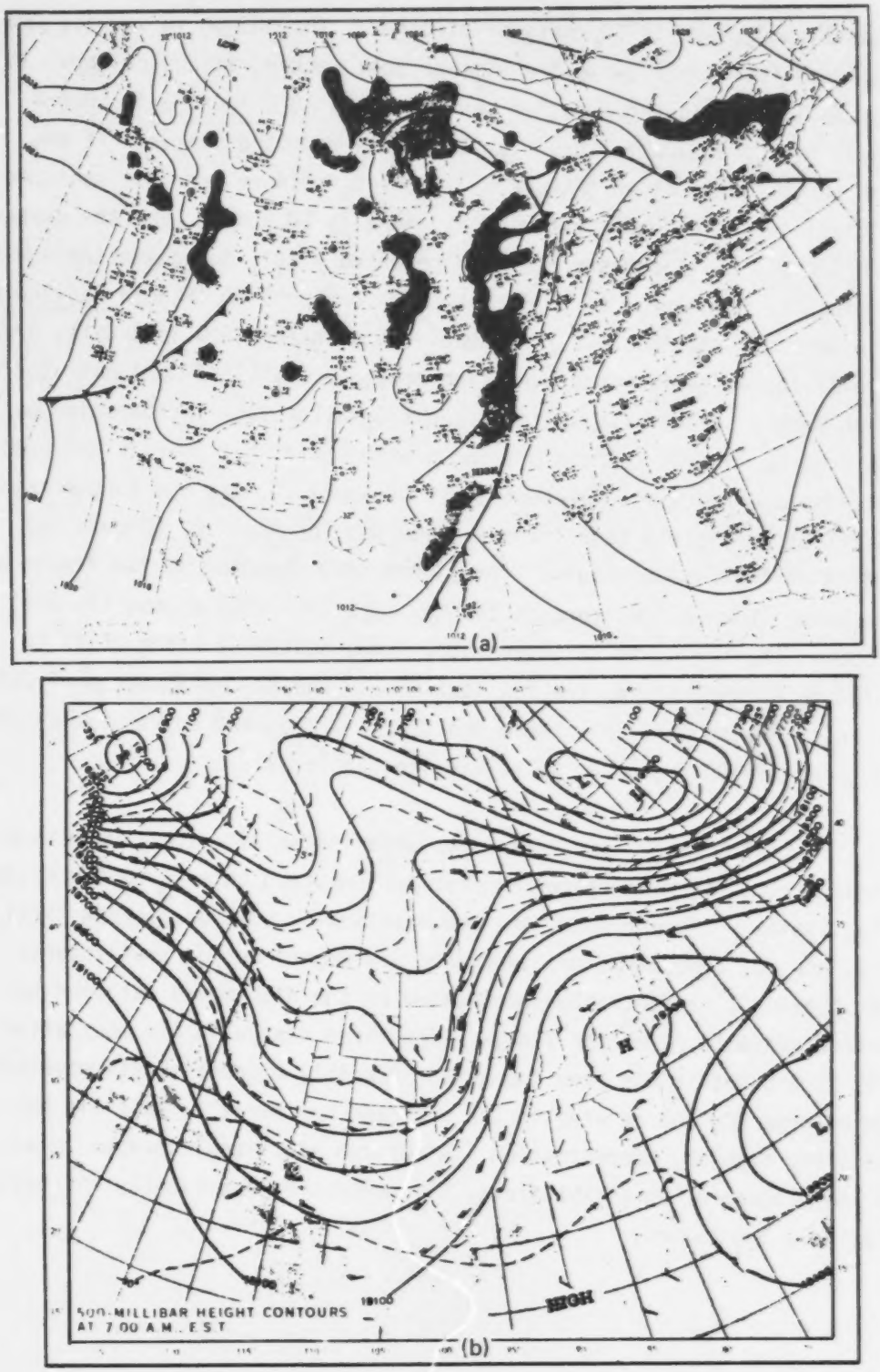

Figure 3. Daily weather maps for 4/18/76. (a) Surface weather map. (b) 500 mb map.

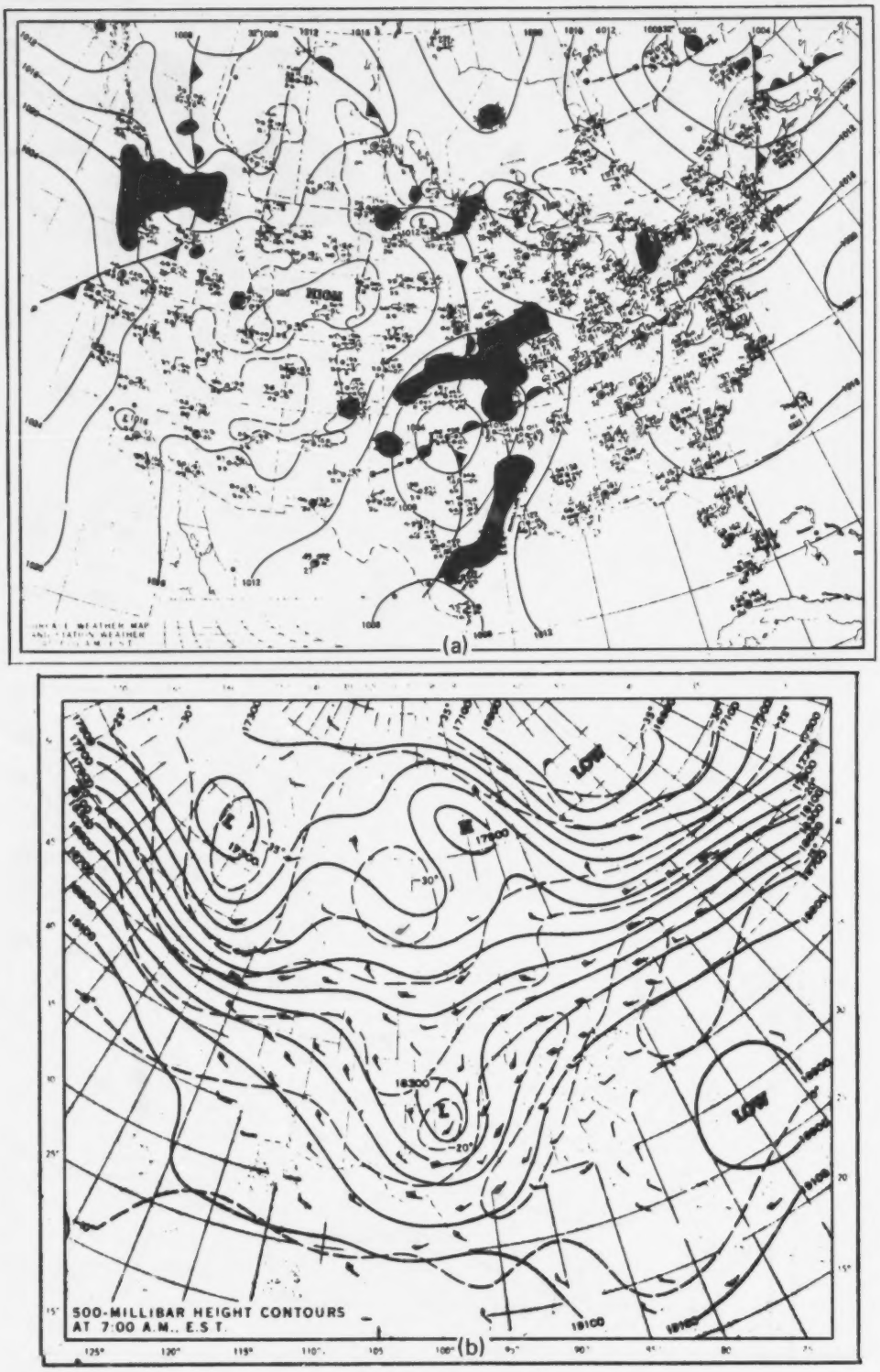

Figure 4. Daily weather maps for 4/20/76. (a) Surface weather map. (b) 500 mb map.

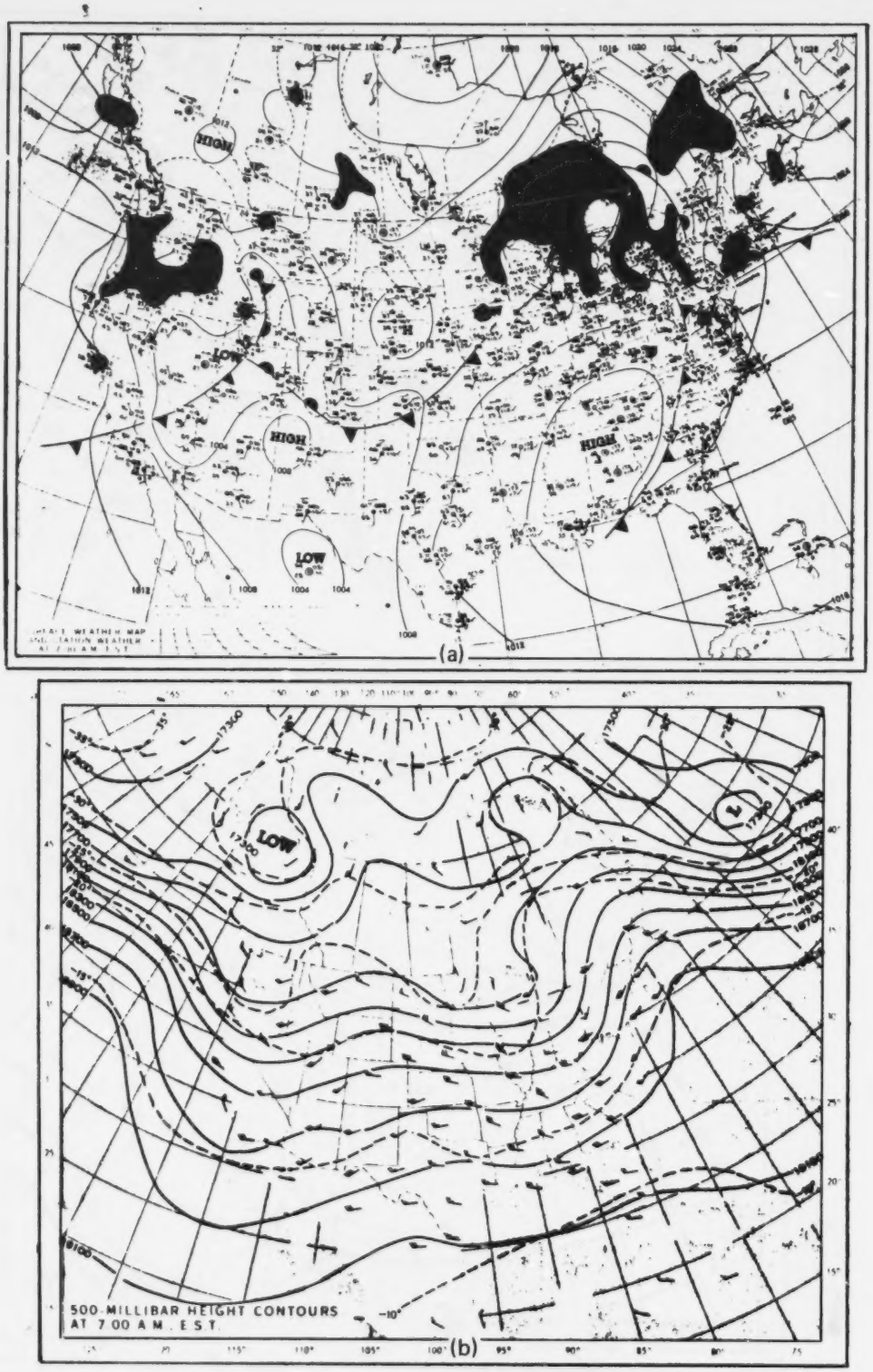

Figure 5. Daily weather maps for 4/22/76. (a) Surface weather map. (b) 500 mb map.

TRAJECTORY CALCULATIONS

Trajectory calculations based on rawinsonde data gathered every 12 hours, are indicators of transport winds. Although trajectories are determined objectively, they are only approximations of the true air flow. If the input data is non-representative (for example, based on radiosonde data taken during a frontal passage), or lacking at a key station, the calculated trajectory could be misleading. The trajectories discussed for a specific day, following the SO_4 sampling schedule, are for 7 p.m. (evening) on the previous day and 7 a.m. (morning) on the listed day.

The analyses for April 14 (Figure 6a) indicate that the New York City area received air from the west during the evening of April 13 and the morning of April 14. Trajectories were respectively 700 and 1000+ km long.

The analyses for April 15 (Figure 6b) show air arriving from a more southerly direction than that for April 14. Both the evening and morning trajectory was 700 km long or longer. The shift in direction from the previous day not only denotes the different source areas, but also reveals that the air mass centered over Canada on April 12 was modified by an influx of warm air from the south.

On April 16 (Figure 6c) the 48-hour trajectory for the evening period was over 1200 km long and traveled up the east coast. However, an examination of the input data disclosed that data for the lowest 1000 m for the New York City radiosonde station were missing. Thus, the calculation was based primarily on low level data for surrounding sites and the resulting trajectory appeared to be misleading. The morning trajectory was over 2000 km long and originated over the Gulf of Mexico.

On April 17 (Figure 6d) flows for the evening and morning were from the west; each was 800 km long or longer.

Trajectories for April 18 (Figure 6e) were among the shortest of this episodic period, but still 600 km long or longer. The evening flow was from

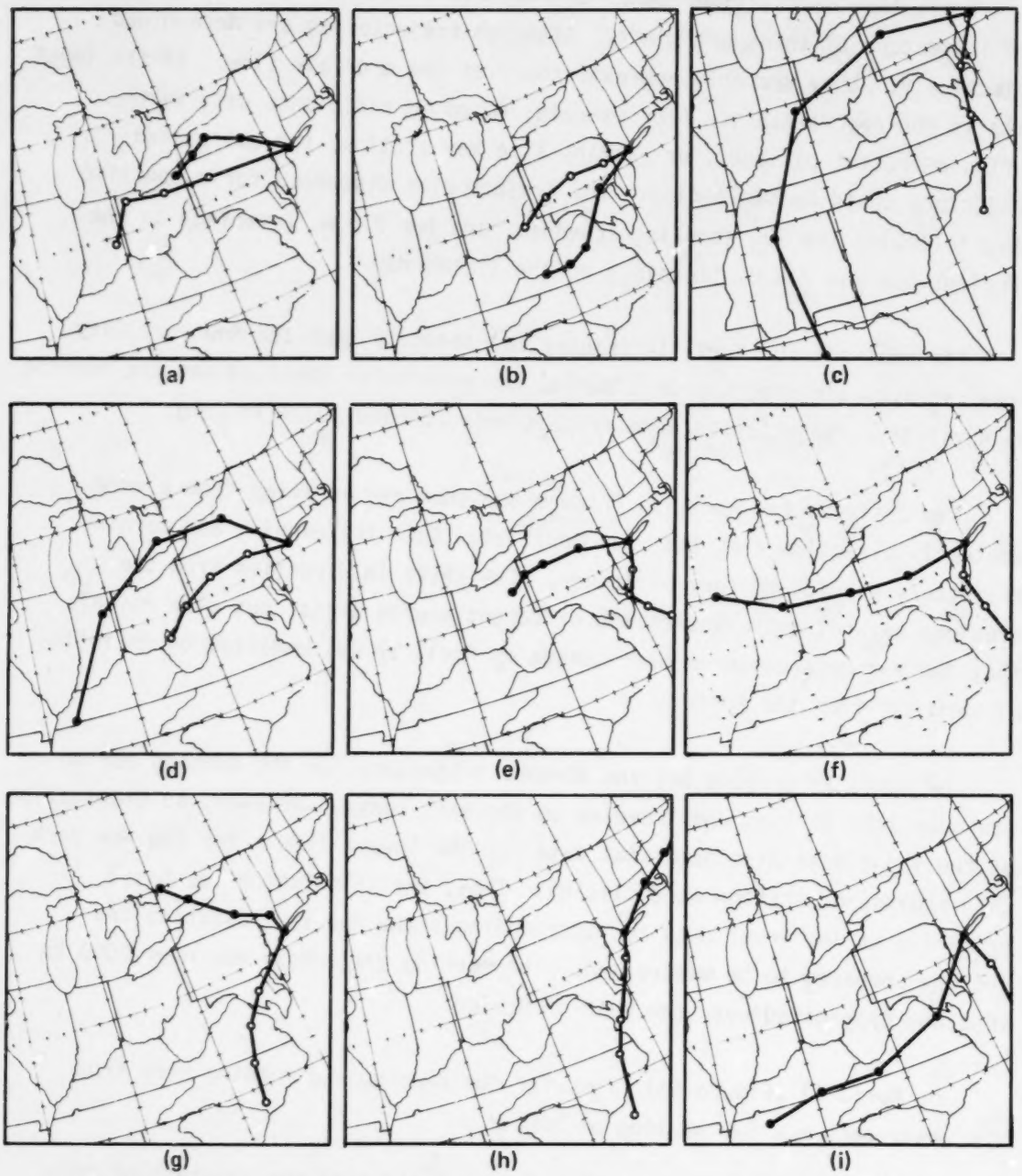

Figure 6. Trajectories associated with sulfate concentrations in New York City area, 4/14-22/76. (a) 4/14/76 (b) 4/15/76 (c) 4/16/76 (d) 4/17/76 (e) 4/18/76 (f) 4/19/76 (g) 4/20/76 (h) 4/21/76 (i) 4/22/76

the ocean and along the coast to the south. The morning trajectory brought in air from the west.

The evening trajectory for April 19 (Figure 6f) illustrates a directional flow and length similar to April 18. The morning trajectory (April 19) shows a flow from western areas with a length exceeding 1500 km.

The trajectories for April 20 (Figure 6g) show the effects of a frontal passage through New York City in the morning (Figure 4). The evening trajectory showed a pre-frontal flow from the south and morning trajectory a post-frontal flow from the northwest. The evening air traveled more than 1000 km and moved over the Richmond to New York corridor. The morning trajectory showed movement over northwestern New York and a major source area in southern Ontario[23], and was slightly shorter than the evening trajectory.

Trajectories on April 21 (Figure 6h) reveal air from widely separated areas. Each trajectory is at least 900 km long. Flow in the evening was along the east coast and from the south; a reverse flow occurred in the morning.

On April 22, the evening trajectory (Figure 6i) was only 24 hours long since the 36-hour and 48-hour locations were off the plotting diagram. Evening flow was from the ocean and covered 600 km in 24 hours. Morning flow originated over land and traversed over 1500 km in 48 hours. The widely separated upwind areas for each trajectory were due to fronts approaching New York City at 7 a.m. (Figure 4) which passed through on April 22.

Although a slow moving high pressure area was associated with this SO_4 episode, all the trajectories were long. The shortest 48-hour trajectories were over 600 km; long range transport occurred continuously throughout the episode. No single general source area was upwind of the City area throughout the episode or for any major part of it.

SULFATE CONCENTRATIONS IN UPWIND AREAS

The SO_4 data from upwind source areas came from numerous air quality sampling groups. The data in Table 4 came from the State air pollution control agencies in Maryland, New York, and Ohio and list the 24-hour concentrations recorded on April 12 and 18. Figure 7 shows the locations of stations in the NASN and their corresponding concentrations for April 18, plus the concentrations observed at five stations in the Province of Ontario. Figure 8 depicts the names and locations of air quality stations in Ontario Province; their concentrations for April 12 to 22 are listed in Table 5. Table 6 lists the SO_4 concentrations recorded from April 12 to 20 at individuals locations in West Virginia and at groups of stations in the TVA network (Alabama, Kentucky, Illinois, Tennessee, and Virginia).

The trajectories ending in New York City on April 14 (Figure 6a) reveal that the predominant upwind areas on April 12 and 13 were Ohio and New York State. Sulfate concentrations at upwind locations on April 12 (Table 4) were low; thus, the potential for long range transport of high sulfate concentrations was negligible and the New York City area generally had low concentrations. The area to the southwest, extending to West Virginia and Virginia, was upwind of New York City during the 48 hours prior to April 15 (Figure 6b). Limited data for this period from Wellsburg, West Virginia indicated increasing concentrations in the upwind area (Table 6). The evening trajectory for April 16 (Figure 6c) according to available calculations, was along the east coast; there were no SO_4 data for upwind locations. However, the morning trajectory showed the TVA area as upwind on April 15 with high SO_4 concentrations (Table 6). Upwind areas for April 17 were: 1) West Virginia and Pennsylvania producing evening air for New York City; and 2) the Toledo-Detroit area, southern Ontario, and New York State with air arriving in the morning. The Parkersburg, West Virginia data (Table 6) indicate the evening trajectory could have brought in high SO_4 concentrations. In addition, Ontario data (Table 5) indicate morning trajectories possibly containing SO_4 burdened air. Both trajectories for April 18 (Figure 6e) were relatively short and lacked SO_4 data for upwind locations

TABLE 4. 24-HOUR SULFATE CONCENTRATIONS ($\mu g/m^3$) IN MARYLAND, NEW YORK, AND OHIO, 4/12 AND 4/18/76

Station	Date	
	4/12	4/18
Maryland		
Baltimore	5	26
Cambridge		26
Hagerstown	5	20
Salisbury	6	26
New York		
Albany	6	26
Binghamton		16
Buffalo	8	14
Jamestown	6	16
Massena	5	14
Ohio		
Akron	2	16
Ashtabula	6	17
Barberton	2	16
Cambell	6	37
Canton	3	16
Cleveland	6	13
Columbus	7	11
Dayton	8	13
Norwood	2	12
Sandusky	7	11
Struthers	6	37
Toledo	6	29

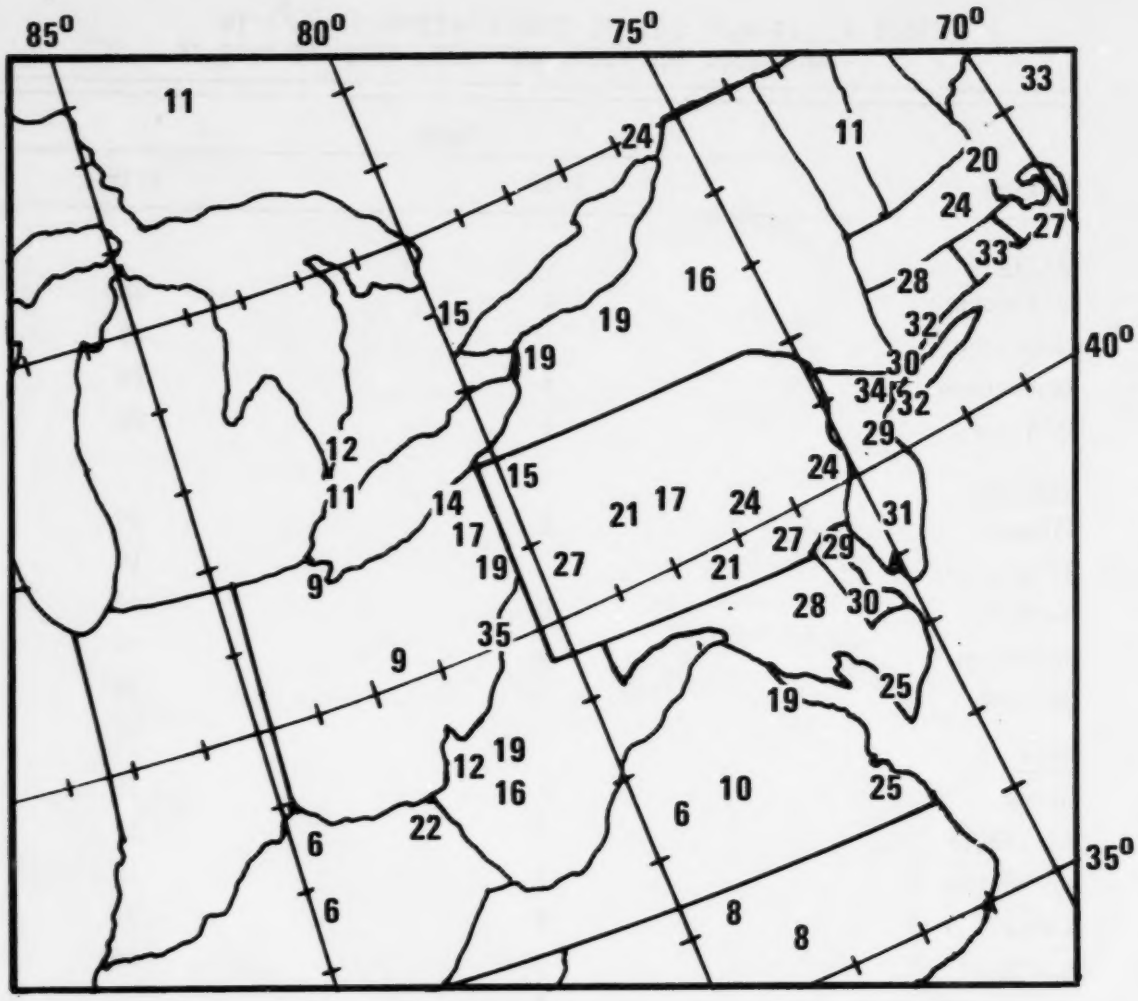

Figure 7. Sulfate concentrations ($\mu g/m^3$) in the area surrounding New York City, 4/18/76.

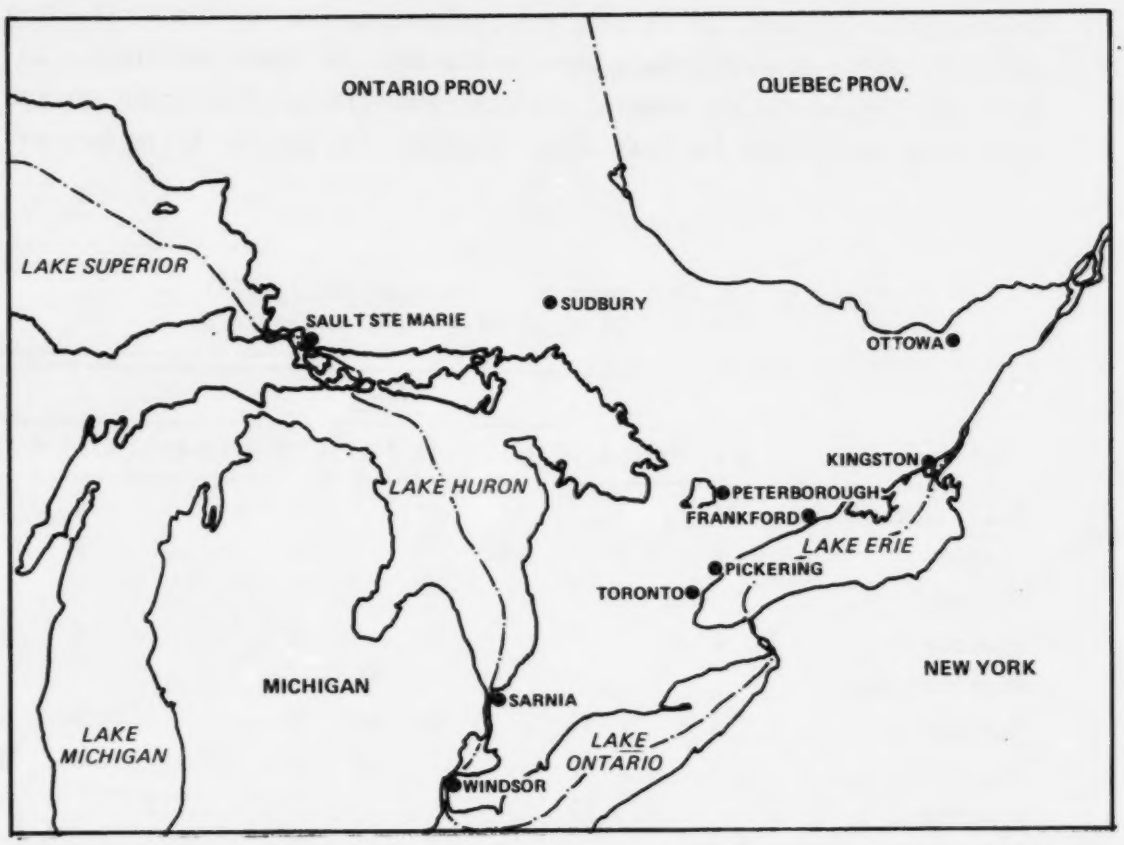

Figure 8. Sulfate sampling sites of Ontario Ministry of the Environment and Ontario Hydro.

on April 16 and 17. However, there were abundant data for April 18 (Tables 4 and 5, Figure 7) revealing an extensive area of high concentrations in the northeastern United States and Ontario. There was a possible influx of high SO_4 concentrations into the New York City area from upwind sources on April 18. However, transport was an insufficient explanation for the simultaneous influx of such high SO_4 concentrations at all these sites. Concentrations exceeding 20 $\mu g/m^3$ were recorded in Ontario, Ohio, New York, Massachusetts, New Jersey, Pennsylvania, Delaware, Maryland, Virginia, and West Virginia. Due to the extensive area of high concentrations surrounding New York City on April 18, trajectories for April 19 and 20 (Figures 6f and 6g) had to show sources of high SO_4 concentrations were upwind of New York City. Trajectories for April 21 (Figure 6h) indicate upwind locations all along the Atlantic Coast; however, there were no SO_4 data for these locations. On April 22 (Figure 6i) the evening trajectory originated from ocean sources; data were unavailable for that area. However, the morning trajectory of

TABLE 5. 24-HOUR SULFATE CONCENTRATIONS ($\mu g/m^3$) FOR THE PROVINCE OF ONTARIO 4/12-22/76*

	Date										
Station	4/12	4/13	4/14	4/15	4/16	4/17	4/18	4/19	4/20	4/21	4/22
Sault Ste. Marie	14			11			4			6	
Sarnia	6			9			12			7	
Sudbury	3						11				
Windsor	6						11			4	
Peterborough						28					
Toronto	4	6	11		12	16	15			5	8
Pickering	3	5	9			15	15	10		7	8
Frankford			11						2		8
Kingston	7						24				
Ottawa	9						17				

* Courtesy of Ontario Hydro.

April 22 showed movement over the TVA area on April 20, and that upwind area (Table 6) had high SO_4 concentrations. Thus, long range transport may have been moving SO_4 toward New York City on April 22, but rainfall may have limited its concentration.

TABLE 6. 24-HOUR SULFATE CONCENTRATIONS ($\mu g/m^3$) IN WEST VIRGINIA AND THE TENNESSEE VALLEY AUTHORITY (TVA) NETWORK, 4/12-20/76

	Date								
Location	4/12	4/13	4/14	4/15	4/16	4/17	4/18	4/19	4/20
West Virginia									
Beckley	4	4						13	
Huntington	6								
Parkersburg				13					
Wellsburg	9	10						27	
TVA Network*									
11 stations			11						
2 stations				10					
1 station					11				
41 stations						7			
2 stations								10	
11 stations									12

* Averages for all stations on a day.

OZONE DATA

The maximum hourly ozone concentrations observed at sites in and near the New York City area from April 14 to 22, 1976, are listed in Table 7. Prior to the promulgation by EPA of the new ozone standard (12 pphm) on January 26, 1979, the standard was 8 pphm. Using 8 pphm as a reference, only one station in the New York City area had a high concentration on April 14. On both April 15 and 16 three of the eight sites had high concentrations while on April 17 and 18 all stations had high concentrations. On

April 19 only half of the sites (none in New York State) had high concentrations; while on April 20, the number of sites with high concentrations was seven. The ozone episode ended on April 21, when all the stations showed concentrations of 8 pphm or less.

TABLE 7. MAXIMUM HOURLY OZONE CONCENTRATIONS (pphm) IN THE NEW YORK CITY AREA, 4/76

Station	Date								
	4/14	4/15	4/16	4/17	4/18	4/19	4/20	4/21	4/22
Bridgeport, CT	5	7	7	11	20	12	12	5	5
Danbury, CT	7	10	10	21	19	23	10	7	4
Groton, CT	9	12	10	11	13	13	10	6	5
Hartford, CT	6	10	7	13	20	21	10	8	5
Babylon, NY	6	7	10	18	21	8	12	6	3
Hempstead, NY	5	5	4	15	18	6	9	8	3
Mamaroneck, NY	6	3	6	12	12	5	6	3	3
New York, NY	7	5	4	19	19	4	15	2	3

High SO_4 and high O_3 concentrations, including peak concentrations of both pollutants, occurred almost simultaneously. Abundant sunshine was a possible contributor (Table 3) to the photochemical production of both pollutants; however, O_3 levels were normal when the SO_4 episode developed. The O_3 episode appeared to terminate a day earlier than the SO_4 episode.

COMPARISON OF PREVIOUS AIR POLLUTION STUDIES TO OUR RESULTS

The investigators[2] of the high SO_4 concentrations of the NASN data for April 18, 1976, and the accompanying meteorological phenomena concluded that a major contributing factor was the warm high pressure area that was moving slowly across the eastern United States. Using this warm air mass as a criterion for determining the beginning and end of the SO_4 episode, the duration of the episode could not be determined. (The investigators had

insufficient data for determining the period representing the SO_4 sample). The Daily Weather Maps show that it was April 16, 1976, before the air mass coming from Canada was modified. This air mass was moved out of the New York City area by a front on the morning of April 20. From the overall weather pattern showing only relatively small changes from April 17 to 19, one could assume that the April 18 SO_4 concentration was representative of all 3 days; thus, the intensity and duration of the worst condition can be inferred.

A highlight of the ozone investigation[14] over the April 12 to 23 period noted that areas of low visibility generally coincided with areas of elevated ozone under specific conditions. Earlier investigators[10,24] showed good agreement between movements of high sulfate concentrations and areas of restricted visibility and the ozone investigators[14] attempted a similar technique. The report[14] did not consider the possibility that areas of high SO_4 concentrations corresponded to areas of high O_3[4,5]. Table 3 shows that the New York City area had restricted visibility from April 15 to 22 which practically coincided with periods of high ozone and high sulfate. In addition, the area of high SO_4 concentrations over the northeastern United States on April 18 (Figure 7) corresponded to high O_3 concentrations on April 18 and restricted visibility on April 19[14]. (There was no restricted visibility map for April 18). Although these comparisons are limited, they do indicate that correspondence between areas of high ozone concentrations and areas of restricted visibility possibly resulted from the presence of high SO_4 concentrations over designated areas. Since visibility restrictions are usually caused by aerosols the size of sulfate particles[25,26] and not by gases such as ozone, it seems more likely that sulfates rather than ozone were responsible.

Due to the discontinuous SO_4 sampling procedure the strongest statement derived is the supposition that SO_4 rather than O_3 was the major cause of the visibility restrictions over the northeastern United States from April 14 to 22, 1976. Until SO_4 is sampled on a continuous basis it will be very difficult to accurately evaluate the effect of SO_4 on air quality and the effect of related pollutants.

SECTION 5

SUMMARY

The SO_4 concentrations at all four CHAMP stations in the New York City area exceeded 10 $\mu g/m^3$ from April 15 to 21, 1976. During much of the episode concentrations were several times greater than those typical for April. These concentrations first exceeded 10 $\mu g/m^3$ on April 15, increased for several days, peaked on April 18 or 19, decreased for a few days, and fell below 10 $\mu g/m^3$ on April 22. The NASN stations in the New York City area, operating every twelfth day, monitored SO_4 near the peak of the episode on April 18, and had comparable concentrations to those observed in the CHAMP network.

The meteorological phenomena typical of the period were: high temperatures (mid-80s to 90°F), abundant sunshine (96% or more daily), relatively low average dew point temperatures (mid-50s°F) and relative humidities (few $\geq$70%), and a slow moving high pressure area.

The episode did not terminate with a frontal passage on April 20, but terminated with an active front which passed through the area bringing in a fresh polar air mass on April 22; rain and very low clouds accompanied the second front.

Air parcels between the surface and 1000 m could have moved into the New York City area from as far away as 2000 km in 48 hours (based on trajectory analyses) and not less than 600 km away; long range transport occurred continuously during the episode. Sulfate data available for upwind locations shown by the trajectories indicated high concentrations in those locations which could have been transported to the New York City area. Unfortunately these SO_4 data were limited and need further verification with

continuous sampling at locations upwind of areas with high SO_4 concentrations.

Analyses of O_3 data from the New York City area reveal O_3 concentrations exceeding 8 pphm occurring concurrently with high SO_4 concentrations. The initial high concentration of each pollutant was April 15. Their concentrations each peaked simultaneously; however, there was a difference in that markedly lower O_3 concentrations accompanied the air mass change on April 20 while the SO_4 concentrations remained high.

An earlier investigation[2] of NASN data for April 18 reported that the warm slow moving air mass over the eastern United States was a factor in the SO_4 episode. Since this air persisted from April 16 to 20 while high SO_4 concentrations persisted from April 15 to 21, other meteorological phenomena must have contributed to some of the high concentrations. Overall: 1) there was insufficient information concerning which period the one day NASN sample represented, and 2) the one-day-in-six observational program is inadequate for relating meteorological phenomena with the initiation and termination of a prolonged episode.

The ozone investigation[14] evaluating meteorological data for April 12-23 concluded that areas of low visibility generally coincided with areas of elevated ozone concentrations. However, when the available but limited SO_4 data from the CHAMP stations for the entire period, the NASN stations on April 18, the TVA plus several State networks in the eastern United States, and the Province of Ontario were compared, it appeared that all areas with high SO_4 concentrations closely corresponded to areas of restricted visibility. It is impossible to say which pollutant contributed to the reduced visibility. Until SO_4 is monitored on a continuous basis, evaluating the effects of SO_4 and other similarly produced pollutants on visibility will remain difficult.

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